

## Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector

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# Search for neutral Higgs bosons of the minimal supersymmetric standard model in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



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**ABSTRACT:** A search for the neutral Higgs bosons predicted by the Minimal Supersymmetric Standard Model (MSSM) is reported. The analysis is performed on data from proton-proton collisions at a centre-of-mass energy of 8 TeV collected with the ATLAS detector at the Large Hadron Collider. The samples used for this search were collected in 2012 and correspond to integrated luminosities in the range 19.5–20.3 fb<sup>−1</sup>. The MSSM Higgs bosons are searched for in the  $\tau\tau$  final state. No significant excess over the expected background is observed, and exclusion limits are derived for the production cross section times branching fraction of a scalar particle as a function of its mass. The results are also interpreted in the MSSM parameter space for various benchmark scenarios.

**KEYWORDS:** Hadron-Hadron Scattering

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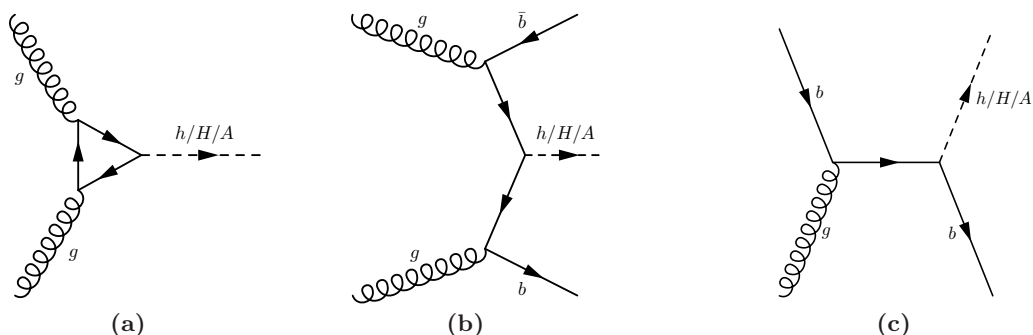
## 1 Introduction

The discovery of a scalar particle at the Large Hadron Collider (LHC) [1, 2] has provided important insight into the mechanism of electroweak symmetry breaking. Experimental studies of the new particle [3–7] demonstrate consistency with the Standard Model (SM) Higgs boson [8–13]. However, it remains possible that the discovered particle is part of an extended scalar sector, a scenario that is favoured by a number of theoretical arguments [14, 15].

The Minimal Supersymmetric Standard Model (MSSM) [16–20] is an extension of the SM, which provides a framework addressing naturalness, gauge coupling unification, and the existence of dark matter. The Higgs sector of the MSSM contains two Higgs doublets, which results in five physical Higgs bosons after electroweak symmetry breaking. Of these bosons, two are neutral and CP-even ( $h$ ,  $H$ ), one is neutral and CP-odd ( $A$ ),<sup>1</sup> and the remaining two are charged ( $H^\pm$ ). At tree level, the mass of the light scalar Higgs boson,  $m_h$ , is restricted to be smaller than the  $Z$  boson mass,  $m_Z$ . This bound is weakened due to

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<sup>1</sup>By convention the lighter CP-even Higgs boson is denoted  $h$ , the heavier CP-even Higgs boson is denoted  $H$ . The masses of the three bosons are denoted in the following as  $m_h$ ,  $m_H$  and  $m_A$  for  $h$ ,  $H$  and  $A$ , respectively.



**Figure 1.** Example Feynman diagrams for (a) gluon fusion and (b)  $b$ -associated production in the four-flavour scheme and (c) five-flavour scheme of a neutral MSSM Higgs boson.

radiative corrections up to a maximum allowed value of  $m_h \sim 135$  GeV. Only two additional parameters are needed with respect to the SM at tree level to describe the MSSM Higgs sector. These can be chosen to be the mass of the CP-odd Higgs boson,  $m_A$ , and the ratio of the vacuum expectation values of the two Higgs doublets,  $\tan \beta$ . Beyond lowest order, the MSSM Higgs sector depends on additional parameters, which are fixed at specific values in various MSSM benchmark scenarios. For example, in the  $m_h^{\max}$  scenario the radiative corrections are chosen such that  $m_h$  is maximized for a given  $\tan \beta$  and  $M_{\text{SUSY}}$  [21, 22].<sup>2</sup> This results for  $M_{\text{SUSY}} = 1$  TeV in  $m_h \sim 130$  GeV for large  $m_A$  and  $\tan \beta$ . In addition, in the same region the heavy Higgs bosons,  $H$ ,  $A$  and  $H^\pm$ , are approximately mass degenerate and  $h$  has properties very similar to a SM Higgs boson with the same mass. This feature is generic in the MSSM Higgs sector: a decoupling limit exists defined by  $m_A \gg m_Z$  in which the heavy Higgs bosons have similar masses and the light CP-even Higgs boson in practice becomes identical to a SM Higgs boson with the same mass.

The discovery of a SM-like Higgs boson, with mass that is now measured to be  $125.36 \pm 0.37$  (stat)  $\pm 0.18$  (syst) GeV [24], has prompted the definition of additional MSSM scenarios [23]. Most notably, the  $m_h^{\text{mod}+}$  and  $m_h^{\text{mod}-}$  scenarios are similar to the  $m_h^{\max}$  scenario, apart from the fact that the choice of radiative corrections is such that the maximum light CP-even Higgs boson mass is  $\sim 126$  GeV. This choice increases the region of the parameter space that is compatible with the observed Higgs boson being the lightest CP-even Higgs boson of the MSSM with respect to the  $m_h^{\max}$  scenario. There are many other MSSM parameter choices beyond these scenarios that are also compatible with the observed SM Higgs boson, for instance, refs. [25, 26].

The couplings of the MSSM Higgs bosons to down-type fermions are enhanced with respect to the SM for large  $\tan \beta$  values resulting in increased branching fractions to  $\tau$  leptons and  $b$ -quarks, as well as a higher cross section for Higgs boson production in association with  $b$ -quarks. This has motivated a variety of searches in  $\tau\tau$  and  $b\bar{b}$  final states at LEP [27], the Tevatron [28–30] and the LHC [31–33].

<sup>2</sup>The supersymmetry scale,  $M_{\text{SUSY}}$ , is defined here as the mass of the third generation squarks following refs. [21–23].

This paper presents the results of a search for a neutral MSSM Higgs boson in the  $\tau\tau$  decay mode using  $19.5\text{--}20.3\text{ fb}^{-1}$  of proton-proton collision data collected with the ATLAS detector [34] in 2012 at a centre-of-mass energy of 8 TeV. Higgs boson production through gluon fusion or in association with  $b$ -quarks is considered (see figure 1), with the latter mode dominating for high  $\tan\beta$  values. The results of the search are interpreted in various MSSM scenarios.

The ATLAS search for the SM Higgs boson in the  $\tau\tau$  channel [35] is similar to that described here. Important differences between the two searches are that they are optimized for different production mechanisms and Higgs boson mass ranges. Additionally, the three Higgs bosons of the MSSM, which can have different masses, are considered in this search. In particular the couplings to  $b$ -quarks and vector bosons are different between the SM and MSSM. The  $b$ -associated production mode is dominant for the  $H$  and  $A$  bosons and is enhanced for the  $h$  boson with respect to the SM for large parts of the MSSM parameter space. Furthermore, the coupling of the  $H$  boson to vector bosons is suppressed with respect to those for a SM Higgs boson with the same mass and the coupling of the  $A$  boson to vector bosons is zero at lowest order, due to the assumption of CP symmetry conservation. Hence, vector boson fusion production and production in association with a vector boson, which contribute significantly to the SM Higgs boson searches, are much less important with respect to the SM. Finally, for high  $m_A$  the search for the heavy  $H$  and  $A$  bosons is more sensitive in constraining the MSSM parameter space than the search for the  $h$  boson. As a consequence, this search has little sensitivity to the production of a SM Higgs boson with a mass around 125 GeV. For consistency, the SM Higgs signal is not considered part of the SM background, as the MSSM contains a SM-like Higgs boson for large parts of the parameter space.

## 2 The ATLAS detector

The ATLAS experiment [34] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near  $4\pi$  coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range<sup>3</sup>  $|\eta| < 2.5$ . It consists of silicon pixel, silicon micro-strip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic (iron/scintillator-tile) calorimeter covers the central pseudorapidity range ( $|\eta| < 1.7$ ). The end-cap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to  $|\eta| = 4.9$ . The muon spectrometer surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each. Its bending power is in the range

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<sup>3</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upwards. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

2.0–7.5 Tm. It includes a system of precision tracking chambers and fast detectors for triggering. A three-level trigger system is used to select events. The first-level trigger is implemented in hardware. It is designed to use a subset of the detector information to reduce the accepted rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the accepted event rate to 400 Hz on average, depending on the data-taking conditions, during 2012.

### 3 Data and Monte Carlo simulation samples

The data used in this search were recorded by the ATLAS experiment during the 2012 LHC run with proton-proton collisions at a centre-of-mass energy of 8 TeV. They correspond to an integrated luminosity of 19.5–20.3 fb<sup>-1</sup>, depending on the search channel.

Simulated samples of signal and background events were produced using various event generators. The presence of multiple interactions occurring in the same or neighbouring bunch crossings (pile-up) was accounted for, and the ATLAS detector was modelled using GEANT4 [36, 37].

The Higgs boson production mechanisms considered in this analysis are gluon fusion and  $b$ -associated production. The cross sections for these processes were calculated using HIGLU [38], GGH@NNLO [39] and SUSHI [39–54]. For  $b$ -associated production, four-flavour [55, 56] and five-flavour [44] cross-section calculations are combined [57]. The masses, couplings and branching fractions of the Higgs bosons are computed with FEYN-HIGGS [50, 51, 53]. Gluon fusion production is simulated with POWHEG BOX 1.0 [58], while  $b$ -associated production is simulated with SHERPA 1.4.1 [59]. For a mass of  $m_A = 150$  GeV and  $\tan\beta = 20$ , the ratio of the gluon fusion to  $b$  associated production modes is approximately 0.5 for  $A$  and  $H$  production and three for  $h$  production. For a mass of  $m_A = 300$  GeV and  $\tan\beta = 30$ , the ratio of production modes becomes approximately 0.1 for  $A$  and  $H$  production and 50 for  $h$  production. For both samples the CT10 [60] parton distribution function set is used. Signal samples are generated using the  $A$  boson production mode at discrete values of  $m_A$ , with the mass steps chosen by taking the  $\tau\tau$  mass resolution into account. The signal model is then constructed by combining three mass samples, one for each of the  $h$ ,  $H$  and  $A$  bosons, with appropriately scaled cross sections and branching fractions. The cross sections and branching fractions, as well as the masses of the  $h$  and  $H$  bosons, depend on  $m_A$ ,  $\tan\beta$  and the MSSM scenario under study. The differences in the kinematic properties of the decays of CP-odd and CP-even Higgs bosons are expected to be negligible for this search. Thus the efficiencies and acceptances from the  $A$  boson simulated samples are applicable to all neutral Higgs bosons.

Background samples of  $W$  and  $Z$  bosons produced in association with jets are produced using ALPGEN 2.14 [61], while the high-mass  $Z/\gamma^*$  tail is modelled separately using PYTHIA8 [62, 63] since in the high-mass range the current analysis is rather insensitive to the modelling of  $b$ -jet production.  $WW$  production is modelled with ALPGEN and  $WZ$  and  $ZZ$  production is modelled with HERWIG 6.520 [64]. The simulation of top pair production uses POWHEG and MC@NLO 4.01 [65], and single-top processes are generated

with ACERMC 3.8 [66]. All simulated background samples use the CTEQ6L1 [67] parton distribution function set, apart from MC@NLO, which uses CT10.

For all the simulated event samples, the parton shower and hadronization are simulated with HERWIG, PYTHIA8 or SHERPA. PYTHIA8 is used for POWHEG-generated samples, SHERPA for the  $b$ -associated signal production and HERWIG for the remaining samples. Decays of  $\tau$  leptons are generated with TAUOLA [68], SHERPA or PYTHIA8. PHOTOS [69] or SHERPA provide additional radiation from charged leptons.

$Z/\gamma^* \rightarrow \tau\tau$  events form an irreducible background that is particularly important when considering low-mass Higgs bosons ( $m_A \lesssim 200$  GeV). It is modelled with  $Z/\gamma^* \rightarrow \mu^+\mu^-$  events from data, where the muon tracks and the associated calorimeter cells are replaced by the corresponding simulated signature of a  $\tau$  lepton decay. The two  $\tau$  leptons are simulated by TAUOLA. The procedure takes into account the effect of  $\tau$  polarization and spin correlations [70]. In the resulting sample, the  $\tau$  lepton decays and the response of the detector are modelled by the simulation, while the underlying event kinematics and all other properties are obtained from data. This  $\tau$ -embedded  $Z/\gamma^* \rightarrow \mu^+\mu^-$  sample is validated as described in refs. [31, 35]. The  $\mu\mu$  event selection requires two isolated muons in the rapidity range  $|\eta| < 2.5$ , where the leading muon has  $p_T > 20$  GeV, the subleading muon  $p_T > 15$  GeV and the invariant mass is in the range  $m_{\mu\mu} > 40$  GeV. This results in an almost pure  $Z/\gamma^* \rightarrow \mu^+\mu^-$  sample, which, however, has some contribution from  $t\bar{t}$  and diboson production. The contamination from these backgrounds that pass the original  $\mu\mu$  event selection and, after replacement of the muons by tau leptons, enter the final event selection are estimated using simulation. Further details can be found in section 6.  $Z/\gamma^* \rightarrow \tau\tau$  events in the invariant mass range  $m_{\tau\tau} < 40$  GeV are modelled using ALPGEN simulated events.

## 4 Object reconstruction

Electron candidates are formed from energy deposits in the electromagnetic calorimeter associated with a charged-particle track measured in the inner detector. Electrons are selected if they have a transverse energy  $E_T > 15$  GeV, lie within  $|\eta| < 2.47$ , but outside the transition region between the barrel and end-cap calorimeters ( $1.37 < |\eta| < 1.52$ ), and meet the “medium” identification requirements defined in ref. [71]. Additional isolation criteria, based on tracking and calorimeter information, are used to suppress backgrounds from misidentified jets or semileptonic decays of heavy quarks. In particular, the sum of the calorimeter deposits in a cone of size  $\Delta R = 0.2$  around the electron direction is required to be less than 6 (8)% of the electron  $E_T$  for the  $\tau_{\text{lep}}\tau_{\text{had}}$  ( $\tau_{\text{lep}}\tau_{\text{lep}}$ ) final state. Similarly, the scalar sum of the transverse momentum of tracks with  $p_T > 1$  GeV in a cone of size  $\Delta R = 0.4$  with respect to the electron direction is required to be less than 6% of the electron  $E_T$ .

Muon candidates are reconstructed by associating an inner detector track with a muon spectrometer track [72]. For this analysis, the reconstructed muons are required to have a transverse momentum  $p_T > 10$  GeV and to lie within  $|\eta| < 2.5$ . Additional track-quality and track-isolation criteria are required to further suppress backgrounds from cosmic rays, hadrons punching through the calorimeter, or muons from semileptonic decays of heavy quarks. The muon calorimetric and track isolation criteria use the same cone sizes and



generally the same threshold values with respect to the muon  $p_T$  as in the case of electrons — only for the case of the  $\tau_{\text{lep}}\tau_{\text{lep}}$  final state is the muon calorimetric isolation requirement changed to be less than 4% of the muon momentum.

Jets are reconstructed using the anti- $k_t$  algorithm [73] with a radius parameter  $R = 0.4$ , taking topological clusters [74] in the calorimeter as input. The jet energy is calibrated using a combination of test-beam results, simulation and *in situ* measurements [75]. Jets must satisfy  $E_T > 20$  GeV and  $|\eta| < 4.5$ . To reduce the effect of pile-up, it is required that, for jets within  $|\eta| < 2.4$  and  $E_T < 50$  GeV, at least half of the transverse momentum, as measured by the associated charged particles, be from particles matched to the primary vertex.<sup>4</sup>

A multivariate discriminant is used to tag jets, reconstructed within  $|\eta| < 2.5$ , originating from a  $b$ -quark [76]. The  $b$ -jet identification has an average efficiency of 70% in simulated  $t\bar{t}$  events, whereas the corresponding light-quark jet misidentification probability is approximately 0.7%, but varies as a function of the jet  $p_T$  and  $\eta$  [77].

Hadronic decays of  $\tau$  leptons ( $\tau_{\text{had}}$ ) [78] are reconstructed starting from topological clusters in the calorimeter. A  $\tau_{\text{had}}$  candidate must lie within  $|\eta| < 2.5$ , have a transverse momentum greater than 20 GeV, one or three associated tracks and a charge of  $\pm 1$ . Information on the collimation, isolation, and shower profile is combined into a multivariate discriminant against backgrounds from jets. Dedicated algorithms that reduce the number of electrons and muons misreconstructed as hadronic  $\tau$  decays are applied. In this analysis, two  $\tau_{\text{had}}$  identification selections are used — “loose” and “medium” — with efficiencies of about 65% and 55%, respectively.

When different objects selected according to the criteria mentioned above overlap with each other geometrically (within  $\Delta R = 0.2$ ) only one of them is considered. The overlap is resolved by selecting muon, electron,  $\tau_{\text{had}}$  and jet candidates in this order of priority.

The missing transverse momentum is defined as the negative vectorial sum of the muon momenta and energy deposits in the calorimeters [79]. The magnitude of the missing transverse momentum is denoted by  $E_T^{\text{miss}}$ . Clusters of calorimeter-cell energy deposits belonging to jets,  $\tau_{\text{had}}$  candidates, electrons, and photons, as well as cells that are not associated with any object, are treated separately in the missing transverse momentum calculation. The energy deposits in calorimeter cells that are not matched to any object are weighted by the fraction of unmatched tracks associated with the primary vertex, in order to reduce the effect of pile-up on the  $E_T^{\text{miss}}$  resolution. The contributions of muons to missing transverse momentum are calculated differently for isolated and non-isolated muons, to account for the energy deposited by muons in the calorimeters.

## 5 Search channels

The following  $\tau\tau$  decay modes are considered in this search:  $\tau_e\tau_\mu$  (6%),  $\tau_e\tau_{\text{had}}$  (23%),  $\tau_\mu\tau_{\text{had}}$  (23%) and  $\tau_{\text{had}}\tau_{\text{had}}$  (42%), where  $\tau_e$  and  $\tau_\mu$  represent the two leptonic  $\tau$  decay modes and the percentages in the parentheses denote the corresponding  $\tau\tau$  branching fractions. The selections defined for each of the channels and described in sections 5.1–5.3 are such that there are no events common to any two of these channels.

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<sup>4</sup>The primary vertex is taken to be the reconstructed vertex with the highest  $\Sigma p_T^2$  of the associated tracks.



Events are collected using several single- and combined-object triggers. The single-electron and single-muon triggers require an isolated lepton with a  $p_T$  threshold of 24 GeV. The single- $\tau_{\text{had}}$  trigger implements a  $p_T$  threshold of 125 GeV. The following combined-object triggers are used: an electron-muon trigger with lepton  $p_T$  thresholds of 12 GeV and 8 GeV for electrons and muons, respectively, and a  $\tau_{\text{had}}\tau_{\text{had}}$  trigger with  $p_T$  thresholds of 38 GeV for each hadronically decaying  $\tau$  lepton.

With two  $\tau$  leptons in the final state, it is not possible to infer the neutrino momenta from the reconstructed missing transverse momentum vector and, hence, the  $\tau\tau$  invariant mass. Two approaches are used. The first method used is the Missing Mass Calculator (MMC) [80]. This algorithm assumes that the missing transverse momentum is due entirely to the neutrinos, and performs a scan over the angles between the neutrinos and the visible  $\tau$  lepton decay products. The MMC mass,  $m_{\tau\tau}^{\text{MMC}}$ , is defined as the most likely value chosen by weighting each solution according to probability density functions that are derived from simulated  $\tau$  lepton decays. As an example, the MMC resolution,<sup>5</sup> assuming a Higgs boson with mass  $m_A = 150$  GeV, is about 30% for  $\tau_e\tau_\mu$  events. The resolution is about 20% for  $\tau_{\text{lep}}\tau_{\text{had}}$  events ( $\tau_{\text{lep}} = \tau_e$  or  $\tau_\mu$ ) for Higgs bosons with a mass in the range 150 – 350 GeV. The second method uses the  $\tau\tau$  total transverse mass, defined as:

$$m_T^{\text{total}} = \sqrt{m_T^2(\tau_1, \tau_2) + m_T^2(\tau_1, E_T^{\text{miss}}) + m_T^2(\tau_2, E_T^{\text{miss}})} ,$$

where the transverse mass,  $m_T$ , between two objects with transverse momenta  $p_{T1}$  and  $p_{T2}$  and relative angle  $\Delta\phi$  is given by

$$m_T = \sqrt{2p_{T1}p_{T2}(1 - \cos \Delta\phi)} .$$

As an example, the  $m_T^{\text{total}}$  mass resolution assuming a Higgs boson with mass  $m_A = 350$  GeV for  $\tau_{\text{had}}\tau_{\text{had}}$  events is approximately 30%. While the MMC exhibits a better  $\tau\tau$  mass resolution for signal events, multi-jet background events tend to be reconstructed at lower masses with  $m_T^{\text{total}}$ , leading to better overall discrimination between signal and background for topologies dominated by multi-jet background.

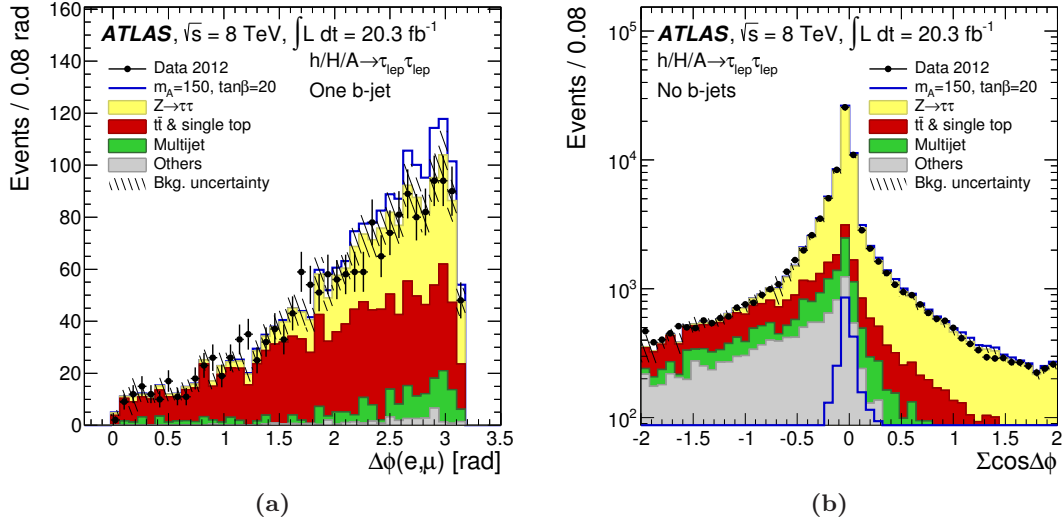
### 5.1 The $h/H/A \rightarrow \tau_e\tau_\mu$ channel

Events in the  $h/H/A \rightarrow \tau_e\tau_\mu$  channel are selected using either single-electron or electron-muon triggers. The data sample corresponds to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . Exactly one isolated electron and one isolated muon of opposite charge are required, with lepton  $p_T$  thresholds of 15 GeV for electrons and 10 GeV for muons. Electrons with  $p_T$  in the range 15–25 GeV are from events selected by the electron-muon trigger, whereas electrons with  $p_T > 25$  GeV are from events selected by the single-electron trigger. Events containing hadronically decaying  $\tau$  leptons, satisfying the “loose”  $\tau_{\text{had}}$  identification criterion, are vetoed.

To increase the sensitivity of this channel, the events are split into two categories based on the presence (“tag category”) or absence (“veto category”) of a  $b$ -tagged jet. The tag

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<sup>5</sup>The resolution of the mass reconstruction is estimated by dividing the root mean square of the mass distribution by its mean.



**Figure 2.** Kinematic distributions for the  $h/H/A \rightarrow \tau_e \tau_\mu$  channel: (a) the  $\Delta\phi(e, \mu)$  distribution after the tag category selection criteria apart from the  $\Delta\phi(e, \mu)$  requirement and (b) the  $\Sigma \cos \Delta\phi$  distribution after the  $b$ -jet veto requirement. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 150 \text{ GeV}$  and  $\tan \beta = 20$ ). In (b) the assumed signal is shown twice: as a distribution in the bottom of the plot and on top of the total background prediction. The background uncertainty includes statistical and systematic uncertainties.

category requires exactly one jet satisfying the  $b$ -jet identification criterion. In addition, a number of kinematic requirements are imposed to reduce the background from top quark decays. The azimuthal angle between the electron and the muon,  $\Delta\phi(e, \mu)$ , must be greater than 2.0 (see figure 2a). The sum of the cosines of the azimuthal angles between the leptons and the missing transverse momentum,  $\Sigma \cos \Delta\phi \equiv \cos(\phi(e) - \phi(E_T^{\text{miss}})) + \cos(\phi(\mu) - \phi(E_T^{\text{miss}}))$ , must be greater than  $-0.2$ . The scalar sum of the  $p_T$  of jets with  $p_T > 30 \text{ GeV}$  must be less than  $100 \text{ GeV}$ . Finally, the scalar sum of the  $p_T$  of the leptons and the  $E_T^{\text{miss}}$  must be below  $125 \text{ GeV}$ . The veto category is defined by requiring that no jet satisfies the  $b$ -jet identification criterion. Because the top quark background is smaller in this category, the imposed kinematic selection requirements,  $\Delta\phi(e, \mu) > 1.6$  and  $\Sigma \cos \Delta\phi > -0.4$  (see figure 2b), are looser than in the tag category.

The most important background processes in this channel are  $Z/\gamma^* + \text{jets}$ ,  $t\bar{t}$ , and multi-jet production. The  $Z/\gamma^* \rightarrow \tau\tau$  background is estimated using the  $\tau$ -embedded  $Z/\gamma^* \rightarrow \mu^+ \mu^-$  sample outlined in section 3. It is normalized using the NNLO  $Z/\gamma^* + \text{jets}$  cross section calculated with FEWZ [81] and a simulation estimate of the efficiency of the trigger, lepton  $\eta$  and  $p_T$ , and identification requirements. The  $t\bar{t}$  background is estimated from simulation with the normalization taken from a data control region enriched in  $t\bar{t}$  events, defined by requiring two  $b$ -tagged jets. The  $W + \text{jet}$  background, where one of the leptons results from a misidentified jet, is estimated using simulation. Smaller backgrounds from single-top and diboson production are also estimated from simulation.

|   | Tag category   | Veto category    |
|---|----------------|------------------|
| Signal ( $m_A = 150$ GeV, $\tan \beta = 20$ ) |                |                  |
| $h \rightarrow \tau\tau$                      | $8.7 \pm 1.9$  | $244 \pm 11$     |
| $H \rightarrow \tau\tau$                      | $65 \pm 14$    | $882 \pm 45$     |
| $A \rightarrow \tau\tau$                      | $71 \pm 15$    | $902 \pm 48$     |
| $Z/\gamma^* \rightarrow \tau\tau$ +jets       | $418 \pm 28$   | $54700 \pm 3800$ |
| Multi-Jet                                     | $100 \pm 21$   | $4180 \pm 670$   |
| $t\bar{t}$ and single top                     | $421 \pm 46$   | $2670 \pm 360$   |
| Others  | $25.8 \pm 7.4$ | $4010 \pm 280$   |
| Total background                              | $965 \pm 59$   | $65500 \pm 3900$ |
| Data  | 904            | 65917            |

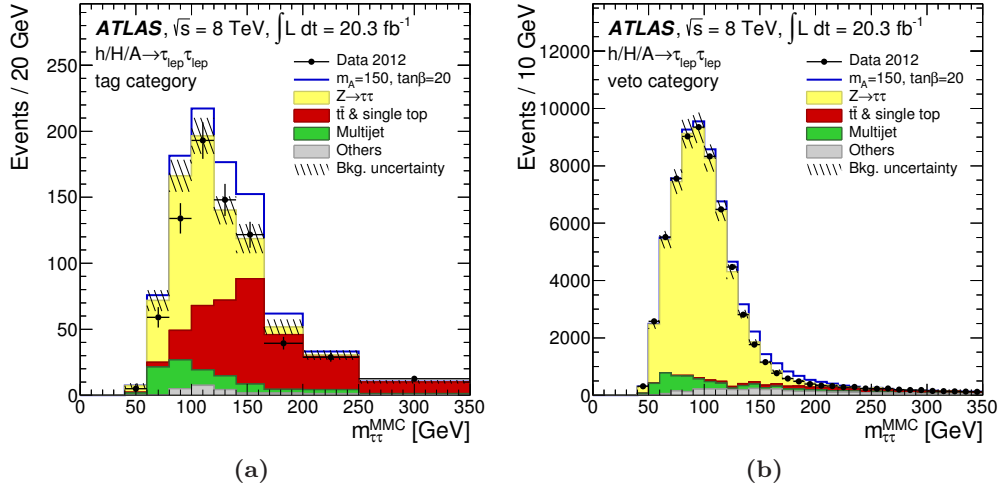
**Table 1.** Number of events observed in the  $h/H/A \rightarrow \tau_e\tau_\mu$  channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice  $m_A = 150$  GeV and  $\tan \beta = 20$ . The row labelled “Others” includes events from diboson production,  $Z/\gamma^* \rightarrow ee/\mu\mu$  and  $W$ +jets production. Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.

The multi-jet background is estimated from data using a two-dimensional sideband method. The event sample is split into four regions according to the charge product of the  $e\mu$  pair and the isolation requirements on the electron and muon. Region  $A$  ( $B$ ) contains events where both leptons pass the isolation requirements and are of opposite (same) charge, while region  $C$  ( $D$ ) contains events where both leptons fail the isolation requirements and are also of opposite (same) charge. This way,  $A$  is the signal region, while  $B$ ,  $C$ , and  $D$  are control regions. Event contributions to the  $B$ ,  $C$  and  $D$  control regions from processes other than multi-jet production are estimated using simulation and subtracted. The final prediction for the multi-jet contribution to the signal region,  $A$ , is given by the background-subtracted data in region  $B$ , scaled by the opposite-sign to same-sign ratio measured in regions  $C$  and  $D$ ,  $r_{C/D} \equiv n_C/n_D$ . Systematic uncertainties on the prediction are estimated from the stability of  $r_{C/D}$  under variations of the lepton isolation requirement.

Table 1 shows the number of observed  $\tau_e\tau_\mu$  events, the predicted background, and the signal prediction for the MSSM  $m_h^{\max}$  scenario [21, 22] parameter choice  $m_A = 150$  GeV and  $\tan \beta = 20$ . The total combined statistical and systematic uncertainties on the predictions are also quoted on table 1. The observed event yields are compatible with the expected yields from SM processes. The MMC mass is used as the discriminating variable in this channel, and is shown in figure 3 for the tag and veto categories separately.

## 5.2 The $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$ channel

Events in the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel are selected using single-electron or single-muon triggers. The data sample corresponds to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . Events are required to contain an electron or a muon with  $p_T > 26$  GeV and an oppositely charged  $\tau_{\text{had}}$

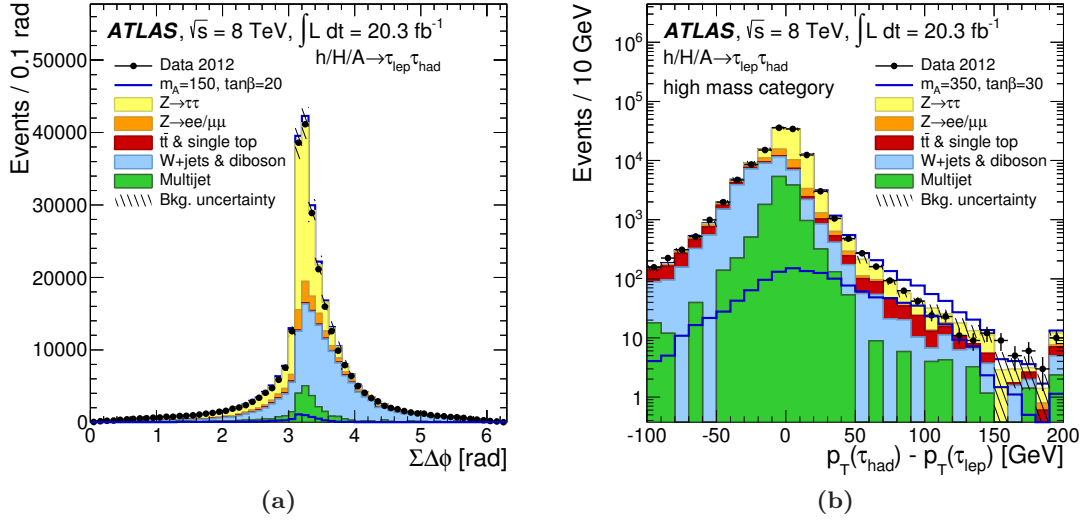


**Figure 3.** MMC mass distributions for the  $h/H/A \rightarrow \tau_e \tau_\mu$  channel. The MMC mass is shown for (a) the tag and (b) the veto categories. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 150$  GeV and  $\tan\beta = 20$ ). The contributions of the diboson,  $Z/\gamma^* \rightarrow ee/\mu\mu$ , and  $W + \text{jets}$  background processes are combined and labelled “Others”. The background uncertainty includes statistical and systematic uncertainties.

with  $p_T > 20$  GeV satisfying the “medium”  $\tau_{\text{had}}$  identification criterion. Events must not contain additional electrons or muons. The event selection is optimized separately for low- and high-mass Higgs bosons in order to exploit differences in kinematics and background composition.

The low-mass selection targets the parameter space with  $m_A < 200$  GeV. It includes two orthogonal categories: the tag category and the veto category. In the tag category there must be at least one jet tagged as a  $b$ -jet. Events that contain one or more jets with  $p_T > 30$  GeV, without taking into account the leading  $b$ -jet, are rejected. In addition, the transverse mass of the lepton and the transverse missing momentum is required to not exceed 45 GeV. These requirements serve to reduce the otherwise dominant  $t\bar{t}$  background. In the veto category there must be no jet tagged as a  $b$ -jet. Two additional selection requirements are applied to reduce the  $W + \text{jets}$  background. First, the transverse mass of the lepton and the missing transverse momentum must be below 60 GeV. Secondly, the sum of the azimuthal angles  $\Sigma\Delta\phi \equiv \Delta\phi(\tau_{\text{had}}, E_T^{\text{miss}}) + \Delta\phi(\tau_{\text{lep}}, E_T^{\text{miss}})$ , must have a value less than 3.3 (see figure 4a). Finally, in the  $\tau_\mu \tau_{\text{had}}$  channel of the veto category, dedicated requirements based on kinematic and shower shape properties of the  $\tau_{\text{had}}$  candidate are applied to reduce the number of muons faking hadronic  $\tau$  lepton decays.

The high-mass selection targets  $m_A \geq 200$  GeV. It requires  $\Sigma\Delta\phi < 3.3$ , in order to reduce the  $W + \text{jets}$  background. The hadronic and leptonic  $\tau$  lepton decays are required to be back-to-back:  $\Delta\phi(\tau_{\text{lep}}, \tau_{\text{had}}) > 2.4$ . In addition, the transverse momentum difference between the  $\tau_{\text{had}}$  and the lepton,  $\Delta p_T \equiv p_T(\tau_{\text{had}}) - p_T(\text{lepton})$ , must be above 45 GeV (see figure 4b). This requirement takes advantage of the fact that a  $\tau_{\text{had}}$  tends to have a higher

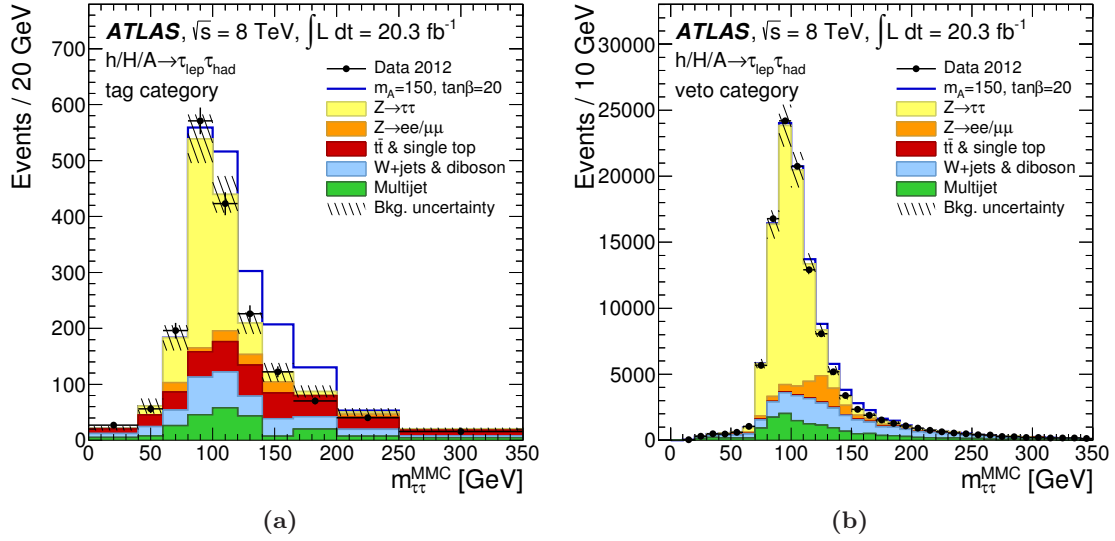


**Figure 4.** Kinematic distributions for the  $h/H/A \rightarrow \tau_{\text{lep}} \tau_{\text{had}}$  channel: (a) the  $\Sigma \Delta \phi$  distribution after the kinematic requirements on the  $\tau_{\text{lep}}$  and  $\tau_{\text{had}}$  and (b) the distribution of  $\Delta p_T \equiv p_T(\tau_{\text{had}}) - p_T(\text{lepton})$  for the high-mass category for the combined  $\tau_e \tau_{\text{had}}$  and  $\tau_\mu \tau_{\text{had}}$  final states. In (b) all the  $\tau_{\text{lep}} \tau_{\text{had}}$  high-mass selection criteria are applied apart from the  $\Delta p_T > 45$  GeV requirement. The data are compared to the background expectation and a hypothetical MSSM signal:  $m_A = 150$  GeV,  $\tan \beta = 20$  for (a) and  $m_A = 350$  GeV,  $\tan \beta = 30$  for (b). The assumed signal is shown twice: as a distribution in the bottom of the plot and on top of the total background prediction. The background uncertainty includes statistical and systematic uncertainties.

visible transverse momentum than a  $\tau_{\text{lep}}$  due to the presence of more neutrinos in the latter decay.

In the low-mass categories, the electron and muon channels are treated separately and combined statistically. For the high-mass category, they are treated as a single channel to improve the statistical robustness.

The most important SM background processes in this channel are  $Z/\gamma^* + \text{jets}$ ,  $W + \text{jets}$ , multi-jet production, top (including both  $t\bar{t}$  and single top) and diboson production. The  $\tau$ -embedded  $Z/\gamma^* \rightarrow \mu^+ \mu^-$  sample is used to estimate the  $Z/\gamma^* \rightarrow \tau\tau$  background. It is normalized in the same way as in the  $\tau_{\text{lep}} \tau_{\text{lep}}$  channel. The rate at which electrons are misidentified as  $\tau_{\text{had}}$ , important mostly for  $Z \rightarrow ee$  decays, was estimated from data in ref. [78]. The contribution of diboson processes is small and estimated from simulation. Events originating from  $W + \text{jets}$ ,  $Z(\rightarrow \ell\ell) + \text{jets}$  ( $\ell = e, \mu$ ),  $t\bar{t}$  and single-top production, in which a jet is misreconstructed as  $\tau_{\text{had}}$ , are estimated from simulated samples with normalization estimated by comparing event yields in background-dominated control regions in data. Separate regions are defined for each of the background sources in each of the low-mass tag, low-mass veto, and high-mass categories. Systematic uncertainties are derived using alternative definitions for the control regions. The multi-jet background is estimated with a two-dimensional sideband method, similar to the one employed for the  $\tau_e \tau_\mu$  channel, using the product of the lepton ( $e$  or  $\mu$ ) and  $\tau_{\text{had}}$  charges and lepton isolation. The



**Figure 5.** The MMC mass distributions for the low-mass categories of the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel. Tag (a) and veto (b) categories are shown for the combined  $\tau_e\tau_{\text{had}}$  and  $\tau_\mu\tau_{\text{had}}$  final states. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 150$  GeV and  $\tan\beta = 20$ ). The background uncertainty includes statistical and systematic uncertainties.

systematic uncertainty on the predicted event yield is estimated by varying the definitions of the regions used, and by testing the stability of the  $r_{C/D}$  ratio across the  $m_{\tau\tau}^{\text{MMC}}$  range.

Table 2 shows the number of observed  $\tau_{\text{lep}}\tau_{\text{had}}$  events, the predicted background, and the signal prediction for the MSSM  $m_h^{\text{max}}$  scenario. The signal MSSM parameters are  $m_A = 150$  GeV,  $\tan\beta = 20$  for the low-mass categories and  $m_A = 350$  GeV,  $\tan\beta = 30$  for the high mass category. The total combined statistical and systematic uncertainties on the predictions are also quoted in table 2. The observed event yields are compatible with the expected yields from SM processes within the uncertainties. The MMC mass is used as the final mass discriminant in this channel and is shown in figures 5 and 6 for the low- and high-mass categories, respectively.

### 5.3 The $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ channel

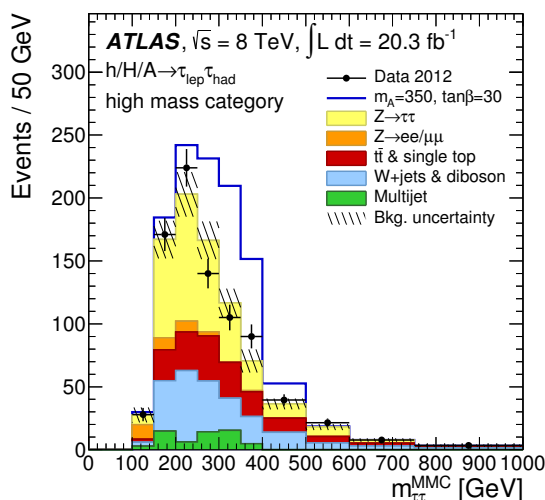
Events in the  $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel are selected using either a single- $\tau_{\text{had}}$  trigger or a  $\tau_{\text{had}}\tau_{\text{had}}$  trigger. The data sample corresponds to an integrated luminosity of  $19.5\text{ fb}^{-1}$ . Events are required to contain at least two  $\tau_{\text{had}}$ , identified using the “loose” identification criterion. If more than two  $\tau_{\text{had}}$  are present, the two with the highest  $p_T$  values are considered. Events containing an electron or muon are rejected to ensure orthogonality with the other channels. The two  $\tau_{\text{had}}$  are required to have  $p_T > 50$  GeV, have opposite electric charges, and to be back-to-back in the azimuthal plane ( $\Delta\phi > 2.7$ ). Two event categories are defined as follows. The single- $\tau_{\text{had}}$  trigger category (STT category) includes the events selected by the single- $\tau_{\text{had}}$  trigger which contain at least one  $\tau_{\text{had}}$  with  $p_T > 150$  GeV (see figure 7a). The  $\tau_{\text{had}}\tau_{\text{had}}$  trigger category (DTT category) includes the events selected by

| Low-mass categories                                |                |                |                  |                  |
|--|----------------|----------------|------------------|------------------|
|  | Tag category   |                | Veto category    |                  |
|  | $e$ channel    | $\mu$ channel  | $e$ channel      | $\mu$ channel    |
| Signal ( $m_A = 150$ GeV, $\tan\beta = 20$ )       |                |                |                  |                  |
| $h \rightarrow \tau\tau$                           | $10.5 \pm 2.8$ | $10.5 \pm 2.6$ | $194 \pm 13$     | $192 \pm 14$     |
| $H \rightarrow \tau\tau$                           | $86 \pm 26$    | $86 \pm 24$    | $836 \pm 60$     | $822 \pm 61$     |
| $A \rightarrow \tau\tau$                           | $94 \pm 29$    | $94 \pm 27$    | $840 \pm 64$     | $825 \pm 62$     |
| $Z \rightarrow \tau\tau$ +jets                     | $403 \pm 39$   | $425 \pm 42$   | $31700 \pm 2800$ | $38400 \pm 3300$ |
| $Z \rightarrow \ell\ell$ +jets ( $\ell = e, \mu$ ) | $72 \pm 24$    | $33 \pm 14$    | $5960 \pm 920$   | $2860 \pm 510$   |
| $W$ +jets  | $158 \pm 44$   | $185 \pm 58$   | $9100 \pm 1300$  | $9800 \pm 1400$  |
| Multi-jet  | $185 \pm 35$   | $66 \pm 31$    | $11700 \pm 490$  | $3140 \pm 430$   |
| $t\bar{t}$ and single top                          | $232 \pm 36$   | $236 \pm 34$   | $533 \pm 91$     | $535 \pm 98$     |
| Diboson  | $9.1 \pm 2.3$  | $10.0 \pm 2.5$ | $466 \pm 40$     | $468 \pm 42$     |
| Total background                                   | $1059 \pm 81$  | $955 \pm 86$   | $59500 \pm 3300$ | $55200 \pm 3600$ |
| Data   | 1067           | 947            | 60351            | 54776            |

| High-mass category                                 |                 |
|--|-----------------|
| Signal ( $m_A = 350$ GeV, $\tan\beta = 30$ )       |                 |
| $h \rightarrow \tau\tau$                           | $5.60 \pm 0.68$ |
| $H \rightarrow \tau\tau$                           | $157 \pm 13$    |
| $A \rightarrow \tau\tau$                           | $152 \pm 13$    |
| $Z \rightarrow \tau\tau$ +jets                     | $380 \pm 50$    |
| $Z \rightarrow \ell\ell$ +jets ( $\ell = e, \mu$ ) | $34.9 \pm 7.3$  |
| $W$ +jets  | $213 \pm 40$    |
| Multi-jet  | $57 \pm 20$     |
| $t\bar{t}$ and single top                          | $184 \pm 26$    |
| Diboson  | $30.1 \pm 4.8$  |
| Total background                                   | $900 \pm 72$    |
| Data   | 920             |

**Table 2.** Numbers of events observed in the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice  $m_A = 150$  GeV,  $\tan\beta = 20$  for the low-mass categories and  $m_A = 350$  GeV,  $\tan\beta = 30$  for the high-mass category. Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.



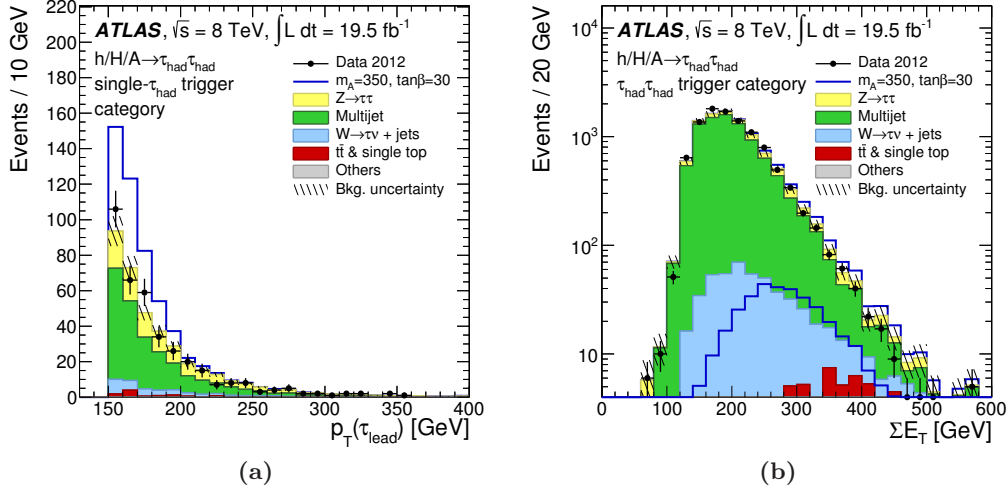


**Figure 6.** The MMC mass distribution for the high-mass category of the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  channel is shown for the combined  $\tau_e\tau_{\text{had}}$  and  $\tau_\mu\tau_{\text{had}}$  final states. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 350$  GeV and  $\tan\beta = 30$ ). The background uncertainty includes statistical and systematic uncertainties.

the  $\tau_{\text{had}}\tau_{\text{had}}$  trigger, with the leading  $\tau_{\text{had}}$  required to have  $p_T$  less than 150 GeV, to ensure orthogonality with the STT category, and with both  $\tau$  leptons satisfying the “medium” identification criterion. In addition, events in the DTT category are required to have  $E_T^{\text{miss}} > 10$  GeV, and the scalar sum of transverse energy of all deposits in the calorimeter to be greater than 160 GeV (see figure 7b).

The dominant background in this channel is multi-jet production and for this reason  $m_T^{\text{total}}$  is used as the final discriminant. Other background samples include  $Z/\gamma^* + \text{jets}$ ,  $W + \text{jets}$ ,  $t\bar{t}$  and diboson.

The multi-jet background is estimated separately for the STT and DTT categories. In the STT category, a control region is obtained by requiring the next-to-highest- $p_T$   $\tau_{\text{had}}$  to fail the “loose”  $\tau_{\text{had}}$  identification requirement, thus obtaining a high-purity sample of multi-jet events. The probability of a jet to be misidentified as a  $\tau_{\text{had}}$  is measured in a high purity sample of dijet events in data, as a function of the number of associated tracks with the jet and the jet  $p_T$ . These efficiencies are used to obtain the shape and the normalization of the multi-jet background from the control region with the next-to-highest- $p_T$   $\tau_{\text{had}}$  that fails the  $\tau_{\text{had}}$  identification requirement. The systematic uncertainty on the method is obtained by repeating the multijet estimation, but requiring either a same-sign or opposite-sign between the two jets. The difference between the calculated efficiencies for the two measurements is then taken as the systematic uncertainty. This procedure has some sensitivity to differences related to whether the jets in the dijet sample are quark- or gluon-initiated. The resulting uncertainty is on average 11%. A two-dimensional sideband method is used in the DTT category by defining four regions based on the charge product of the two  $\tau_{\text{had}}$  and the  $E_T^{\text{miss}} > 10$  GeV requirement. A systematic uncertainty is derived by



**Figure 7.** Kinematic distributions for the  $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel: (a) the transverse momentum of the highest- $p_T$   $\tau_{\text{had}}$  for the STT category and (b) the scalar sum of transverse energy of all deposits,  $\Sigma E_T$ , in the DTT category, before the application of this requirement. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 350$  GeV and  $\tan\beta = 30$ ). The background labelled “Others” includes events from diboson production,  $Z \rightarrow \ell\ell$  and  $W \rightarrow \ell\nu$  with  $\ell = e, \mu$ . In (b) the assumed signal is shown twice: as a distribution in the bottom of the plot and on top of the total background prediction. The background uncertainty includes statistical and systematic uncertainties.

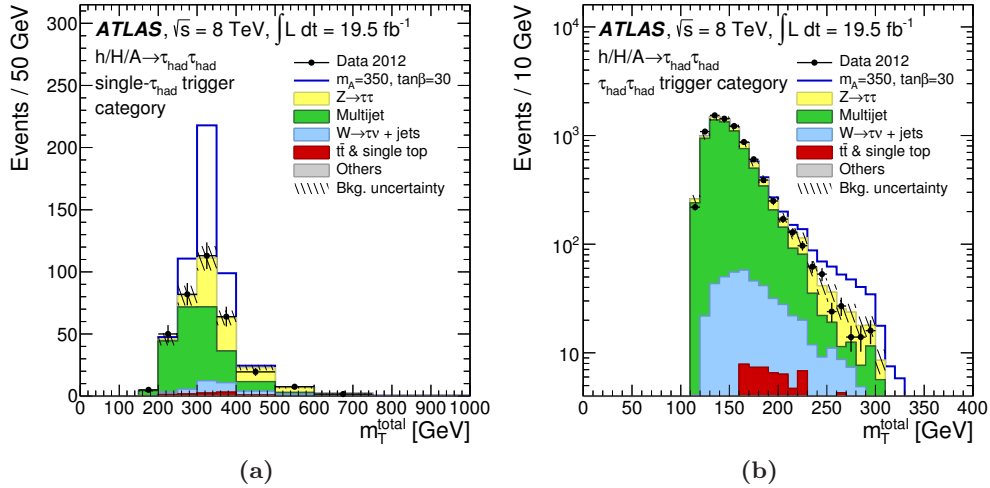
measuring the variation of the ratio of opposite-sign to same-sign  $\tau_{\text{had}}\tau_{\text{had}}$  pairs for different sideband region definitions, as well as across the  $m_T^{\text{total}}$  range, and amounts to 5%.

The remaining backgrounds are modelled using simulation. Non-multi-jet processes with jets misidentified as  $\tau_{\text{had}}$  are dominated by  $W(\rightarrow \tau\nu)+\text{jets}$ . In such events the  $\tau_{\text{had}}$  identification requirements are only applied to the  $\tau_{\text{had}}$  from the  $W$  decay and not the jet that may be misidentified as the second  $\tau_{\text{had}}$ . Instead the event is weighted using misidentification probabilities, measured in a control region in data, to estimate the background yield.  $Z/\gamma^* + \text{jets}$  background is also estimated using simulation. Due to the small number of remaining events after the  $p_T$  thresholds of the  $\tau_{\text{had}}$  trigger requirements, the  $\tau$ -embedded  $Z \rightarrow \mu\mu$  sample is not used.

Table 3 shows the number of observed  $\tau_{\text{had}}\tau_{\text{had}}$  events, the predicted background, and the signal prediction for the MSSM  $m_h^{\text{max}}$  scenario parameter choice  $m_A = 350$  GeV,  $\tan\beta = 30$ . The total combined statistical and systematic uncertainties on the predictions are also quoted in table 3. The observed event yields are compatible with the expected yields from SM processes within the uncertainties. The distributions of the total transverse mass are shown in figure 8 for the STT and the DTT categories separately.

|  | Single- $\tau_{\text{had}}$ trigger<br>(STT) category | $\tau_{\text{had}}\tau_{\text{had}}$ trigger<br>(DTT) category |
|--|---|--|
| Signal ( $m_A = 350$ GeV, $\tan\beta = 30$ ) |   |  |
| $h \rightarrow \tau\tau$                     | $0.042 \pm 0.039$                                     | $11.2 \pm 4.5$   |
| $H \rightarrow \tau\tau$                     | $95 \pm 18$   | $182 \pm 27$   |
| $A \rightarrow \tau\tau$                     | $82 \pm 16$   | $158 \pm 24$   |
| Multi-jet                                    | $216 \pm 25$  | $6770 \pm 430$   |
| $Z/\gamma^* \rightarrow \tau\tau$            | $113 \pm 18$  | $750 \pm 210$  |
| $W(\rightarrow \tau\nu)$ +jets               | $34 \pm 8.1$  | $410 \pm 100$  |
| $t\bar{t}$ and single top                    | $10.2 \pm 4.4$  | $76 \pm 26$  |
| Others                                       | $0.50 \pm 0.20$                                       | $3.40 \pm 0.80$  |
| Total background                             | $374 \pm 32$  | $8010 \pm 490$   |
| Data   | 373   | 8225   |

**Table 3.** Number of events observed in the  $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice  $m_A = 350$  GeV,  $\tan\beta = 30$ . The row labelled “Others” includes events from diboson production,  $Z \rightarrow \ell\ell$  and  $W \rightarrow \ell\nu$  with  $\ell = e, \mu$ . Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.



**Figure 8.** Total transverse mass distributions for (a) STT and (b) DTT categories of the  $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channel. The data are compared to the background expectation and a hypothetical MSSM signal ( $m_A = 350$  GeV and  $\tan\beta = 30$ ). The background labelled “Others” includes events from diboson production,  $Z \rightarrow \ell\ell$  and  $W \rightarrow \ell\nu$  with  $\ell = e, \mu$ . The background uncertainty includes statistical and systematic uncertainties.

## 6 Systematic uncertainties

The event yields for several of the backgrounds in this search are estimated using control samples in data as described in section 5 and their associated uncertainties are discussed there. In this section, the remaining uncertainties are discussed and the overall effect of the systematic uncertainties is presented. Many of the systematic uncertainties affect both the signal and background estimates based on MC. These correlations are used in the limit calculation described in section 7.

Signal cross-section uncertainties are taken from the study in ref. [82]. Typical uncertainty values are in the range 10–15% for gluon fusion and 15–20% for  $b$ -associated production.

The uncertainty on the signal acceptance from the parameters used in the event generation of signal and background samples is also considered. This is done by evaluating the change in acceptance after varying the factorisation and renormalisation scale parameters, parton distribution function choices, and if applicable, conditions for the matching of the partons used in the fixed-order calculation and the parton shower. The uncertainty on the signal acceptance is largest in the tag category for  $b$ -associated production, where it is about 13%.

Uncertainties for single-boson and diboson production cross sections are estimated for missing higher-order corrections, parton distribution functions and the value of the strong coupling constant, and are considered wherever applicable. Acceptance uncertainties for these background processes are estimated in the same way as for signal. The most important theoretical uncertainties on the background are the  $Z$ +jets cross section and acceptance, which affect the normalization by about 7%.

The uncertainty on the integrated luminosity is 2.8%. It is derived, following the same methodology as that detailed in ref. [83], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

The single- $\tau_{\text{had}}$  and  $\tau_{\text{had}}\tau_{\text{had}}$  trigger efficiencies are studied in  $Z \rightarrow \tau\tau$  events. Their uncertainties are in the range 3–25% depending on the number of the tracks matched to the  $\tau_{\text{had}}$ , the  $\tau_{\text{had}}$  pseudorapidity and  $p_{\text{T}}$ , as well as the data-taking period. They are estimated with a method similar to the one in ref. [84] and updated for the 2012 data-taking conditions.

The  $\tau_{\text{had}}$  identification efficiency is measured using  $Z \rightarrow \tau\tau$  events. The uncertainty is in the range 3–10%, depending on the  $\tau_{\text{had}}$  pseudorapidity and the number of tracks matched to the  $\tau$  lepton [78]. Extrapolated uncertainties are used for  $\tau_{\text{had}}$  candidates with transverse momenta above those accessible in  $Z \rightarrow \tau\tau$  events.

The  $\tau_{\text{had}}$  energy scale uncertainty is estimated by propagating the single-particle response to the individual  $\tau_{\text{had}}$  decay products (neutral and charged pions). This uncertainty is in the range 2–4% [85] depending on  $p_{\text{T}}$ , pseudorapidity and the number of associated tracks.

The jet energy scale (JES) and resolution uncertainties are described in refs. [75, 86]. The JES is established by exploiting the  $p_{\text{T}}$  balance between a jet and a reference object

such as a  $Z$  boson or a photon. The uncertainty range is between 3% and 7%, depending on the  $p_T$  and pseudorapidity.

The  $b$ -jet identification efficiency uncertainty range is from 2% to 8%, depending on the jet  $p_T$ . The estimation of this uncertainty is based on a study that uses  $t\bar{t}$  events in data [76].

The  $E_T^{\text{miss}}$  uncertainties are derived by propagating all energy scale uncertainties of reconstructed objects. Additionally, the uncertainty on the scale for energy deposits outside reconstructed objects and the resolution uncertainties are considered [87].

Electron and muon reconstruction, identification, isolation and trigger efficiency uncertainties are estimated from data in refs. [72, 88]. Uncertainties related to the electron energy scale and resolution and to the muon momentum scale and resolution are also estimated from data [72, 89] and taken into account.

Systematic uncertainties associated with the  $\tau$ -embedded  $Z/\gamma^* \rightarrow \mu^+\mu^- + \text{jets}$  data event sample are examined in refs. [31, 35]. Two are found to be the most significant: the uncertainty due to the muon selection, which is estimated by varying the muon isolation requirement used in selecting the  $Z/\gamma^* \rightarrow \mu^+\mu^- + \text{jets}$  events, and the uncertainty from the subtraction of the calorimeter cell energy associated with the muon. The embedded sample contains a small contamination of  $t\bar{t}$  events at high MMC values. This is found to have a non-negligible influence in the  $\tau_{\text{lep}}\tau_{\text{had}}$  tag and high-mass categories only. The effect on the search result is found to be very small in the tag category since other background contributions are dominant in the relevant MMC region. Its effect is taken into account by adding an additional uncertainty of 50% to the  $Z \rightarrow \tau\tau$  background for MMC values exceeding 135 GeV. For the high-mass category, the estimated background level is subtracted from the data and an uncertainty contribution of the same size is applied.

The relative effect of each of the systematic uncertainties can be seen by their influence on the signal strength parameter,  $\mu$ , defined as the ratio of the fitted to the assumed signal cross section times branching fraction (see also section 7). The effects of the most important sources of systematic uncertainty are shown for two signal assumptions: table 4 shows a low-mass pseudoscalar boson hypothesis ( $m_A = 150$  GeV,  $\tan\beta = 5.7$ ) and table 5 a high-mass pseudoscalar boson hypothesis ( $m_A = 350$  GeV,  $\tan\beta = 14$ ). The  $\tan\beta$  values chosen correspond to the observed limits for the respective  $m_A$  assumptions (see section 7). The size of the systematic uncertainty on  $\mu$  varies strongly with  $\tan\beta$ . In these tables, “Multi-jet background” entries refer to uncertainties inherent to the methods used in estimation of the multi-jet background in the various channels of this search. The largest contribution comes from the stability of the ratio of opposite-sign to same-sign events used in the two-dimensional sideband extrapolation method for the multi-jet background estimation.

## 7 Results

The results from the channels studied in this search are combined to improve the sensitivity to MSSM Higgs boson production. Each of the channels used here is optimized for a specific Higgs boson mass regime. In particular, the  $\tau_e\tau_\mu$  channel, the  $\tau_{\text{lep}}\tau_{\text{had}}$  tag category, and the  $\tau_{\text{lep}}\tau_{\text{had}}$  veto category are used for the range  $90 \leq m_A < 200$  GeV. The  $\tau_{\text{lep}}\tau_{\text{had}}$  high mass

| Source of uncertainty  | Uncertainty on $\mu$ (%) |
|--|--------------------------|
| Lepton-to- $\tau_{\text{had}}$ fake rate   | 14                       |
| $\tau_{\text{had}}$ energy scale   | 12                       |
| Jet energy scale and resolution  | 11                       |
| Electron reconstruction & identification   | 8.1                      |
| Simulated backgrounds cross section and acceptance   | 7.5                      |
| Luminosity   | 7.4                      |
| Muon reconstruction & identification   | 7.2                      |
| $b$ -jet identification  | 6.6                      |
| Jet-to- $\tau_{\text{had}}$ fake rate for electroweak processes ( $\tau_{\text{lep}}\tau_{\text{had}}$ ) | 6.2                      |
| Multi-jet background ( $\tau_{\text{lep}}\tau_{\text{lep}}$ , $\tau_{\text{lep}}\tau_{\text{had}}$ )     | 6.1                      |
| Associated with the $\tau$ -embedded $Z \rightarrow \mu\mu$ sample                                       | 5.3                      |
| Signal acceptance  | 2.0                      |
| $e\mu$ trigger   | 1.5                      |
| $\tau_{\text{had}}$ identification   | 0.8                      |

**Table 4.** The effect of the most important sources of uncertainty on the signal strength parameter,  $\mu$ , for the signal hypothesis of  $m_A = 150$  GeV,  $\tan\beta = 5.7$ . For this signal hypothesis only the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  and  $h/H/A \rightarrow \tau_e\tau_\mu$  channels are used.

| Source of uncertainty  | Uncertainty on $\mu$ (%) |
|--|--------------------------|
| $\tau_{\text{had}}$ energy scale   | 15                       |
| Multi-jet background ( $\tau_{\text{had}}\tau_{\text{had}}$ , $\tau_{\text{lep}}\tau_{\text{had}}$ ) | 9.8                      |
| $\tau_{\text{had}}$ identification   | 7.9                      |
| Jet-to- $\tau_{\text{had}}$ fake rate for electroweak processes                                      | 7.6                      |
| $\tau_{\text{had}}$ trigger  | 7.4                      |
| Simulated backgrounds cross section and acceptance   | 6.6                      |
| Signal acceptance  | 4.7                      |
| Luminosity   | 4.1                      |
| Associated with the $\tau$ -embedded $Z \rightarrow \mu\mu$ sample                                   | 1.2                      |
| Lepton identification  | 0.7                      |

**Table 5.** The effect of the most important sources of uncertainty on the signal strength parameter,  $\mu$ , for the signal hypothesis of  $m_A = 350$  GeV,  $\tan\beta = 14$ . For this signal hypothesis only the  $h/H/A \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$  and  $h/H/A \rightarrow \tau_{\text{had}}\tau_{\text{had}}$  channels are used.

category and the  $\tau_{\text{had}}\tau_{\text{had}}$  channel are used for  $m_A \geq 200$  GeV. The event selection in these categories is such that the low mass categories, i.e. those that target  $90 \leq m_A < 200$  GeV, are sensitive to the production of all three MSSM Higgs bosons,  $h$ ,  $H$  and  $A$ . In contrast, the categories that target  $m_A \geq 200$  GeV are sensitive only to  $H$  and  $A$  production.

The parameter of interest in this search is the signal strength,  $\mu$ , defined as the ratio of the fitted signal cross section times branching fraction to the signal cross section times branching fraction predicted by the particular MSSM signal assumption. The value  $\mu = 0$  corresponds to the absence of signal, whereas the value  $\mu = 1$  suggests signal presence as predicted by the theoretical model under study. The statistical analysis of the data employs a binned likelihood function constructed as the product of Poisson probability terms as an estimator of  $\mu$ . Signal and background predictions depend on systematic uncertainties, which are parameterized as nuisance parameters and are constrained using Gaussian functions. The binned likelihood function is constructed in bins of the MMC mass for the  $\tau_e\tau_\mu$  and the  $\tau_{\text{lep}}\tau_{\text{had}}$  channels and in bins of total transverse mass for the  $\tau_{\text{had}}\tau_{\text{had}}$  channel.

Since the data are in good agreement with the predicted background yields, exclusion limits are calculated. The significance of any small observed excess in data is evaluated by quoting  $p$ -values to quantify the level of consistency of the data with the  $\mu=0$  hypothesis. Exclusion limits use the modified frequentist method known as  $\text{CL}_s$  [90]. Both the exclusion limits and  $p$ -values are calculated using the asymptotic approximation [91]. The test statistic used for the exclusion limits derivation is the  $\tilde{q}_\mu$  test statistic and for the  $p$ -values the  $q_0$  test statistic<sup>6</sup> [91].

The lowest local  $p$ -values are calculated assuming a single scalar boson  $\phi$  with narrow natural width with respect to the experimental mass resolution. The lowest local  $p$ -value for the combination of all channels corresponds to 0.20, or 0.8  $\sigma$  in terms of Gaussian standard deviations, at  $m_\phi = 200$  GeV. For the individual channels, the lowest local  $p$ -value in  $\tau_{\text{had}}\tau_{\text{had}}$  is 0.10 (or 1.3  $\sigma$ ) at  $m_\phi = 250$  GeV and for the  $\tau_{\text{lep}}\tau_{\text{had}}$  0.10 (or 1.3  $\sigma$ ) at  $m_\phi = 90$  GeV. In the  $\tau_{\text{lep}}\tau_{\text{lep}}$  channel there is no excess in the mass region used for the combination ( $90 \leq m_\phi < 200$  GeV).

Expected and observed 95% confidence level (CL) upper limits for the combination of all channels are shown in figure 9a for the MSSM  $m_h^{\text{max}}$  scenario with  $M_{\text{SUSY}} = 1$  TeV [21, 22]. In this figure, the theoretical MSSM Higgs cross-section uncertainties are not included in the reported result, but their impact is shown separately, by recalculating the upper

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<sup>6</sup>The definition of the test statistics used in this search is the following:

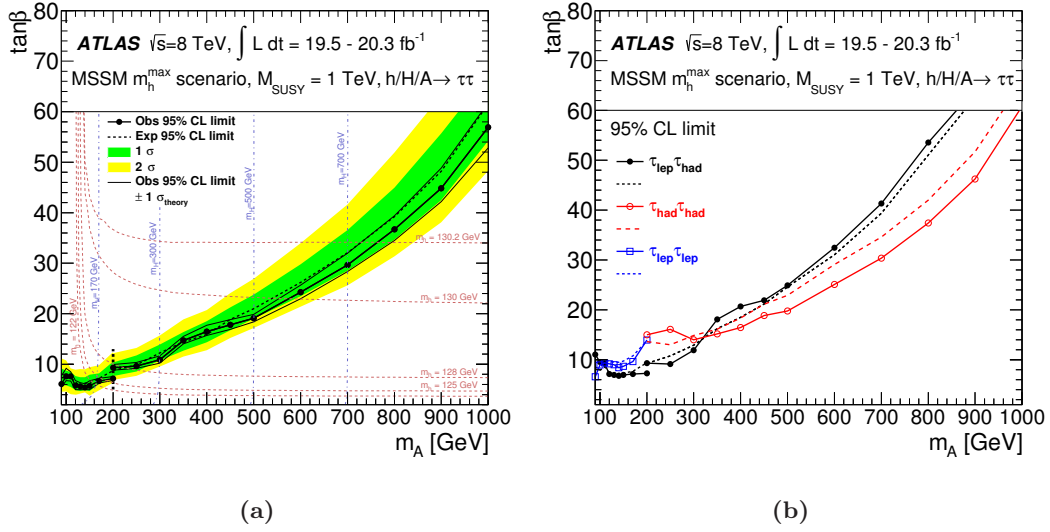
$$\tilde{q}_\mu = \begin{cases} -2 \ln(\mathcal{L}(\mu, \hat{\theta})/\mathcal{L}(0, \hat{\theta})) & \text{if } \hat{\mu} < 0 \\ -2 \ln(\mathcal{L}(\mu, \hat{\theta})/\mathcal{L}(\hat{\mu}, \hat{\theta})) & \text{if } 0 \leq \hat{\mu} \leq \mu \\ 0 & \text{if } \hat{\mu} > \mu \end{cases}$$

and

$$q_0 = \begin{cases} -2 \ln(\mathcal{L}(0, \hat{\theta})/\mathcal{L}(\hat{\mu}, \hat{\theta})) & \text{if } \hat{\mu} \geq 0 \\ 0 & \text{if } \hat{\mu} < 0 \end{cases}$$

where  $\mathcal{L}(\mu, \theta)$  denotes the binned likelihood function,  $\mu$  is the parameter of interest (i.e. the signal strength parameter), and  $\theta$  denotes the nuisance parameters. The pair  $(\hat{\mu}, \hat{\theta})$  corresponds to the global maximum of the likelihood, whereas  $(x, \hat{\theta})$  corresponds to a conditional maximum in which  $\mu$  is fixed to a given value  $x$ .

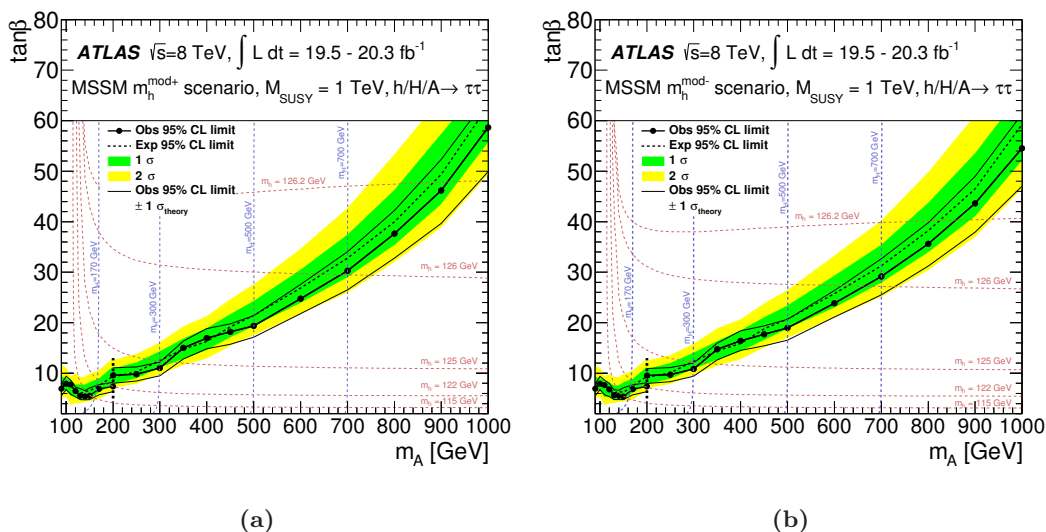




**Figure 9.** Expected (dashed line) and observed (solid line with markers) 95% CL upper limits on  $\tan\beta$  as a function of  $m_A$  for the  $m_h^{\max}$  scenario of the MSSM (a) for the combination of all channels and (b) for each channel separately. Values of  $\tan\beta$  above the lines are excluded. The vertical dashed line at 200 GeV in (a) indicates the transition point between low- and high-mass categories. Lines of constant  $m_h$  and  $m_H$  are also shown in (a) in red and blue colour, respectively. For more information, see text.

limits again after considering the relevant  $\pm 1\sigma$  variations. Figure 9b shows the upper limits for each channel separately for comparison. The best  $\tan\beta$  constraint for the combined search excludes  $\tan\beta > 5.4$  for  $m_A = 140$  GeV, whereas, as an example,  $\tan\beta > 37$  is excluded for  $m_A = 800$  GeV. Figure 9a shows also contours of constant  $m_h$  and  $m_H$  for the MSSM  $m_h^{\max}$  scenario. Assuming that the light CP-even Higgs boson of the MSSM has a mass of about 125 GeV and taking into consideration the 3 GeV uncertainty in the  $m_h$  calculation in the MSSM [23], only the parameter space that is compatible with  $122 < m_h < 128$  GeV is allowed. From this consideration it is concluded that if the light CP-even Higgs boson of the MSSM is identified with the particle discovered at the LHC, then for this particular MSSM scenario  $m_A < 160$  GeV is excluded for all  $\tan\beta$  values. Similarly,  $\tan\beta > 10$  and  $\tan\beta < 4$  are excluded for all  $m_A$  values. Figure 10 shows the expected and observed upper limits for the MSSM  $m_h^{\text{mod}+}$  and  $m_h^{\text{mod}-}$  scenarios [23]. Again, the combination of all channels is shown and the impact of signal cross-section uncertainties is shown separately. Under the assumption that the light CP-even Higgs boson of the MSSM is identified with the particle discovered at the LHC and taking into account the same considerations as in the  $m_h^{\max}$  scenario case, the region with  $m_A < 200$  GeV is excluded for all  $\tan\beta$  values, whereas  $\tan\beta < 5.5$  is excluded for all values of  $m_A$  for both the MSSM  $m_h^{\text{mod}+}$  and  $m_h^{\text{mod}-}$  scenarios.

The outcome of the search is further interpreted in the case of a single scalar boson  $\phi$ , with narrow width relative to the experimental mass resolution, produced in either the gluon fusion or  $b$ -associated production mode and decaying to  $\tau\tau$ . Figure 11 shows 95% CL upper limits on the cross section times the  $\tau\tau$  branching fraction based on this

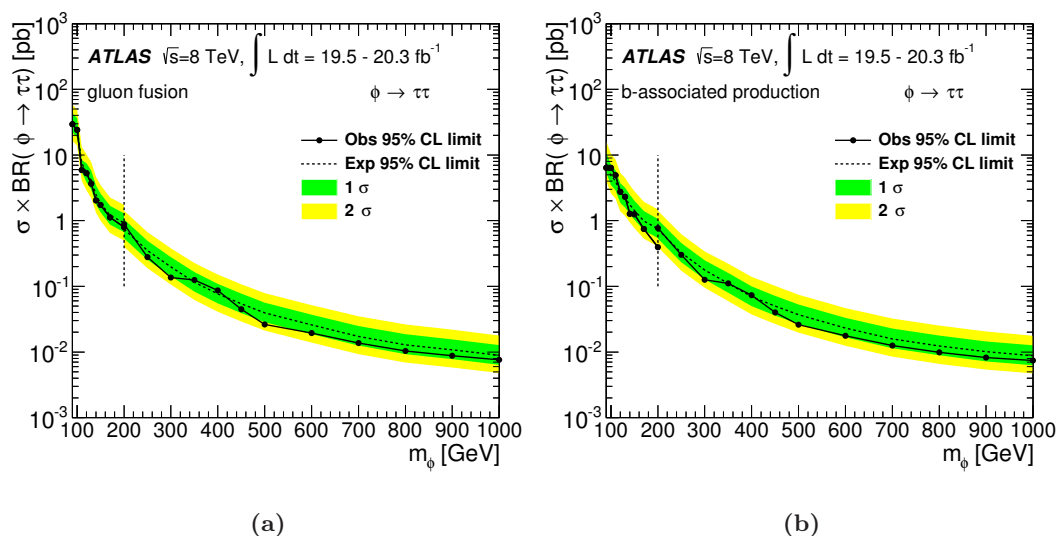


**Figure 10.** Expected (dashed line) and observed (solid line with markers) 95% CL upper limits on  $\tan\beta$  as a function of  $m_A$  for (a) the  $m_h^{\text{mod}+}$  and (b) the  $m_h^{\text{mod}-}$  benchmark scenarios of the MSSM. The same notation as in figure 9a is used.

interpretation. The exclusion limits for the production cross section times the branching fraction for a scalar boson decaying to  $\tau\tau$  are shown as a function of the scalar boson mass. The excluded cross section times branching fraction values range from  $\sigma \times BR > 29 \text{ pb}$  at  $m_\phi = 90 \text{ GeV}$  to  $\sigma \times BR > 7.4 \text{ fb}$  at  $m_\phi = 1000 \text{ GeV}$  for a scalar boson produced via gluon fusion. The exclusion range for the  $b$ -associated production mechanism ranges from  $\sigma \times BR > 6.4 \text{ pb}$  at  $m_\phi = 90 \text{ GeV}$  to  $\sigma \times BR > 7.2 \text{ fb}$  at  $m_\phi = 1000 \text{ GeV}$ .

## 8 Summary

A search is presented for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in proton-proton collisions at the centre-of-mass energy of 8 TeV with the ATLAS experiment at the LHC. The integrated luminosity used in the search is  $19.5\text{--}20.3 \text{ fb}^{-1}$ . The search uses the  $\tau\tau$  final state. In particular, the following cases are considered: one  $\tau$  lepton decays to an electron and the other to a muon ( $\tau_e\tau_\mu$ ), one  $\tau$  lepton decays to an electron or muon and the other hadronically ( $\tau_{\text{lep}}\tau_{\text{had}}$ ) and finally both  $\tau$  leptons decay hadronically ( $\tau_{\text{had}}\tau_{\text{had}}$ ). The sensitivity is improved by performing a categorisation based on expected Higgs boson mass and production mechanisms. The search finds no indication of an excess over the expected background in the channels considered and 95% CL limits are set, which provide tight constraints in the MSSM parameter space. In particular, in the context of the MSSM  $m_h^{\text{max}}$  scenario the lowest  $\tan\beta$  constraint excludes  $\tan\beta > 5.4$  for  $m_A = 140 \text{ GeV}$ . Upper limits for the production cross section times  $\tau\tau$  branching fraction of a scalar boson versus its mass, depending on the production mode, are also presented. The excluded cross section times  $\tau\tau$  branching fraction ranges from about 30 pb to about 7 fb depending on the Higgs boson mass and the production mechanism.



**Figure 11.** Expected (dashed bold line) and observed (solid bold line) 95% CL upper limits on the cross section of a scalar boson  $\phi$  produced via (a) gluon fusion and (b) in association with  $b$ -quarks times the branching fraction into  $\tau$  pairs. The vertical dashed line at 200 GeV indicates the transition point between low- and high-mass categories.

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